Development and Evaluation of Smart Grid

Simulation System with Power Stabilization by EV

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Abstract

Recently, attention has been focused on whether the Smart Grid could work efficiently in an energy network. The subject of our study is the electric vehicle (EV), which has been proposed as a potential chargeable/dischargeable part of the power grid infrastructure. As energy is transferred between an EV and the power grid, it is possible to regulate energy on the entire grid via charging and discharging the EV battery. In the future, it may also be possible to stabilize energy within the system, using information technology control embedded in the network of the Smart Grid. This research is to construct the Smart Grid simulation system to evaluate power flow on such an environment. As a result of the evaluation, the proposed and developed system works to provide us means of a useful evaluation for various cases of the Smart Grid.

Keywords: energy network, EV, simulation system, Smart Grid, Vehicle-to-Grid (V2G)

1. Introduction

Recently, the scarcity of natural resources and rapid increases in energy demands have been raised as worldwide problems; thus, it has become necessary to promote renewable energy generation as a means of energy conservation. As a result, power plants of renewable energies draw attentions such as solar power, wind power, geothermal power, and so on. They are expected not only from the viewpoint of energy demands but also environmental consciousness. However, controlling output power for renewable energy generation is difficult because energy output is subject to violent fluctuations, different from the traditional power source like thermal power, hydroelectric power, and atomic power. To address this issue, attention has been focused on the potential for Smart Grid to work efficiently in energy networks.

While there are various definitions for Smart Grid depending on literatures, a typical idea is to control the power grids by the information and communication technology (ICT) to improve the efficiency of the power grids. It also includes power plants of renewable energies to supplement the traditional power plants in many cases [1]. Although it is preferable to include renewable energies from the viewpoint of energy demands problem, they cannot provide a stable energy as mentioned above. Therefore, information gathered and analyzed based on ICT is used to supply a stable energy in Smart Grid.

As another viewpoint of the energy demands and environmental consciousness, the electric vehicle (EV) is also drawing attention recently. EV is closely related to the Smart Grid. Each EV has a high-capacity battery, which is not only used as a vehicle but is also treated as a power resource that can charge and discharge energy as needed. This energy exchange is referred to as 'Vehicle-to-Grid' (V2G), which is expected to be used as a method of stable energy supply in the Smart Grid.

However, V2G power grids are different from traditional power grids that deliver electricity from power plants to users in a single direction. Power resources in V2G power grids are widely distributed within a given area, and electric transmission is bidirectional. In this case, meticulous control regulation to stabilize power flow is necessary, i.e., it is necessary to monitor the electric potential of each point on the grid, to exchange information through the network and to control the distribution of power sources. In such a case, the Smart Grid is the best platform for gathering and analyzing the information.

In this study, a simulation system is developed as a method to evaluate power control when EVs are connected to the Smart Grid as a power source. First, a power grid simulation environment will be constructed, and the impact of EVs connected to the power grid in this simulated environment will be evaluated. Specifically, we will connect many EVs to the power grid environment, discharged the batteries and monitor the voltage fluctuations at each point. Then, we will prepare some algorithms to determine which EV should be discharged, and evaluate efficacy of electric power stabilization. According to the evaluation, As a result of the evaluation, the proposed and developed system works to provide us means of a useful evaluation for various cases of the Smart Grid.

The remainder of this paper is organized as follows. Section 2 introduces an outline of the Smart Grid and EV. Many previous researches have been already published about Smart Grid and EV, so such references are introduced and our works are justified in this section also. Section 3 summarizes the simulation system architecture constructed in this study. Section 4 describes a model of the distribution network and introduces the implementation of EVs and a solar power plant in an experimental simulation system. Section 5 shows the results of the simulation connecting EVs as a power source to a power grid. Section 6 presents a conclusion and future directions for this research.

2. Background

2.1 Smart Grid

There is no clear definition of the 'Smart Grid'. In a broad sense, this term refers to the electric power system that can coordinate and direct the network of electric power energy. Features of this system include the ability to integrate a large amount of renewable energy, to transmit electricity in both directions at the power grids and to manage information as well as energy.

Figure 1 shows the schematic view of a Smart Grid. Figure 1 is a diagram constructed in reference to official documents from the Ministry of Economy, Trade and Industry [1]. Electric power flow (green line) and information control (blue line) are both represented in Figure 1. The Smart Grid includes a large wind power plant, a large solar power plant and solar panels on each home and building, so that electric power can be transmitted bi-directionally. This feature allows the power grids to accept abundant electric power. However, there is a concern that power in the grids will become erratic. Thus, control using IT, an important feature of the Smart Grid, is needed. The control center connects the power grids and monitors the electric power status of each point on the grids through the network. The control center enables electric power stabilization so that power generation is promoted under conditions of energy scarcity, and electric power is stored in the storage facilities under conditions of energy overabundance. As explained above, the Smart Grid is a technology that stabilizes the complicated flow of electric power using IT control.
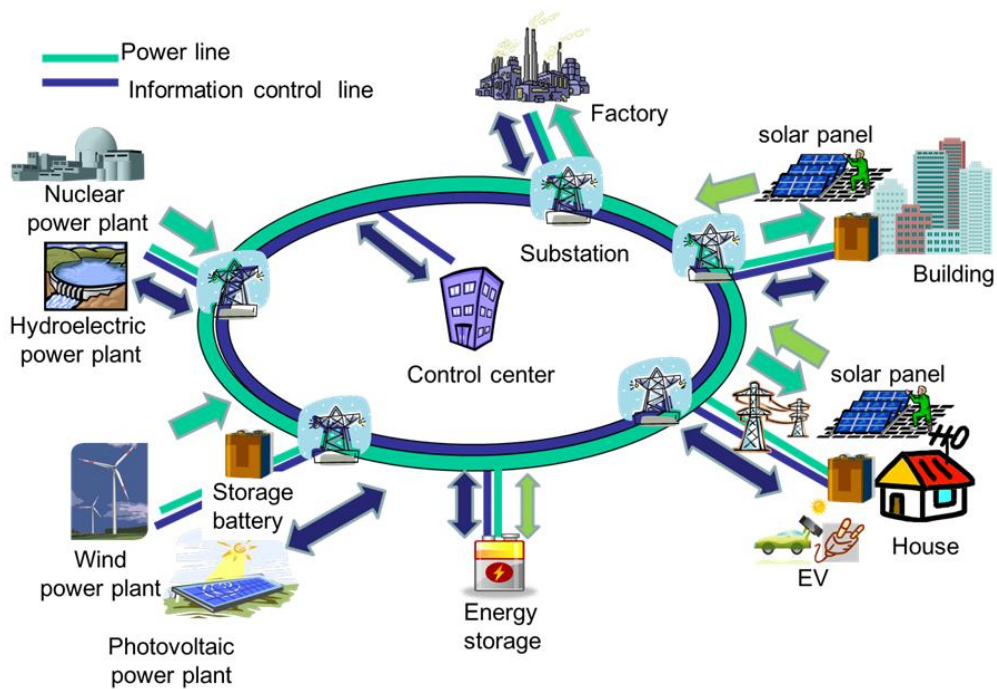
Figure 1. Smart Grid.

2.2 Relationship between EVs and the Smart Grid

Next, we focus on the utilization of EV power in the Smart Grid. The EV is a vehicle that uses an electric motor instead of an internal combustion engine. In this research, we examine the EV as a source of energy supply and demand.

Recently, the EV has been proposed for function of not only a vehicle but also a power resource that can charge and discharge energy as needed. This idea has been disseminated in Smart Grid research studies and referenced by the term 'V2G'. As EV technology has spread, a huge number of batteries have been distributed in a variety of locations. It is possible to adjust the energy within the entire grid so that the EV batteries discharge in the case of energy deficiency on the power grids and electric power is stored in EV batteries in the case of an excess of energy on the power grids.

2.3 Existing Researches about EV and the Electricity Grid

Currently, the Smart Grid is drawing attention in the viewpoint of energy and environment matters. EV is an important factor for the realization of the Smart Grid, as described above. In this case, the use of IT energy stabilization control is indispensable to this system. However, it should be noted that electric power on the grids is subject to violent fluctuations because EVs move freely within the grid. In contrast to a case in which a fixed storage battery is connected to the grid, there are complicated power control issues when EVs are used as a power source because EV batteries are worn out by repeated charging and

discharging cycles excessively.

There are existing researches about EV and electricity grid which have a numeric simulation. One of them discusses about the communication method between grid and EV, in which the media and protocols used in the communication among the elements of the Smart Grid are evaluated [2]. Although this paper provides the evaluation result when EV is used, which is the same with our works, it concentrates mainly on the communication system of the Smart Grid itself.

Another paper discusses the optimization problem about power retail sales and an electric power supply for EVs [3]. This describes mostly the discussion in the viewpoint of business matters. How to realize the eco-system of EVs economically is also important because this requires a new social infrastructure. However, the objective of the evaluation is different from our research works.

The ideal arrangement method of a battery exchange station is discussed and evaluated in [4]. There is an idea in which the battery of EV is exchanged rather than charged in the station. In such a case, what we should consider about becomes a little changed; not only the charge of electricity from the Smart Grid but also the cost of the battery. This is an interesting viewpoint, which should be considered when this style of the EV usage becomes popular.

Another related work is the discussion of the resource that is easy to be affected on the grid [5]. This evaluates the charge of EVs from the Smart Grid based on the lifestyle of people. According to the simulation results, the resources on the Smart Grid should be influenced intensively by the charge of EVs.

The impact of deployment of Plug-in Hybrid Electric Vehicles (PHEVs) on current power distribution network is estimated and discussed in [6]. Supply/demand matching and potential violations of statutory voltage limits, power quality and imbalance are clarified. The impact of charging PHEVs on distribution Grid also evaluated in [7] in order to improve its efficiency. [8] also discusses about the relationship between feeder losses, load factor, and load variance in the context of coordinated PHEV charging. These evaluations assume present electric Grid and investigate the impact of introduction of EVs to the Grid, different from our works that assumes Smart Grid in the near future.

In [9], the potential impact of PHEVs charging on the Smart Grid is investigated. This explores a simulation method that combines Multi-Agent Transport Simulation (MATSim) and PHEV Management and Power System Simulation (PMPSS) so that higher resolution electric demand data can be treated. Although more detailed condition for charging PEVs can be clarified, V2G case is not discussed in this literature.

The basic principles of V2G communication interfaces are described in [10]. Protocol mapping for this purpose is proposed in this work, and sample implementation is shown. However, the performance of the system is not evaluated different from our research works.

Many literatures describes about the Smart Grid and/or EV using a numeric simulation. However, it is difficult to verify how much influence they have to an actual electricity grid. It

is necessary to analyze the voltage value and the power value at each point in detail.

In this paper, the effects of a solar power plant and EVs on power grids are examined via simulations in which the power output of the solar power plant and number and position of EVs discharging at a given time are varied.

3. System Architecture

This section summarizes the electric power system simulator "OpenDSS" used for this system and the simulation system architecture constructed in this study.

3.1 OpenDSS

The constructed experimental environment was based on a simulation platform by Open Distribution System Simulator (OpenDSS) [11]. OpenDSS can manage and analyze objects (lines, buses, power plants, substations, regulators, capacitors, etc.) on the power network constructed by user. Moreover, it is possible to set up the rated voltage, rated current, rated power, rated load, a connection method of each object, and so on. We can set a time unit (yearly, monthly, daily etc.) freely and observe power flow.

3.2 Constructed Smart Grid Simulation System

Figure 2 shows the schematic view of Smart Grid System architecture which was constructed in this research work. First, we set up objects on electricity grids such as EVs and a power plant on OpenDSS, and it calculates the power flow at each point. Next, we constructed the power control system which issues instructions to Objects for electric power stabilization at each point, such as management of data of electric power situation and the method of electric discharge of EV. Finally, we combined these two systems, and the Smart Grid simulation system is constructed.
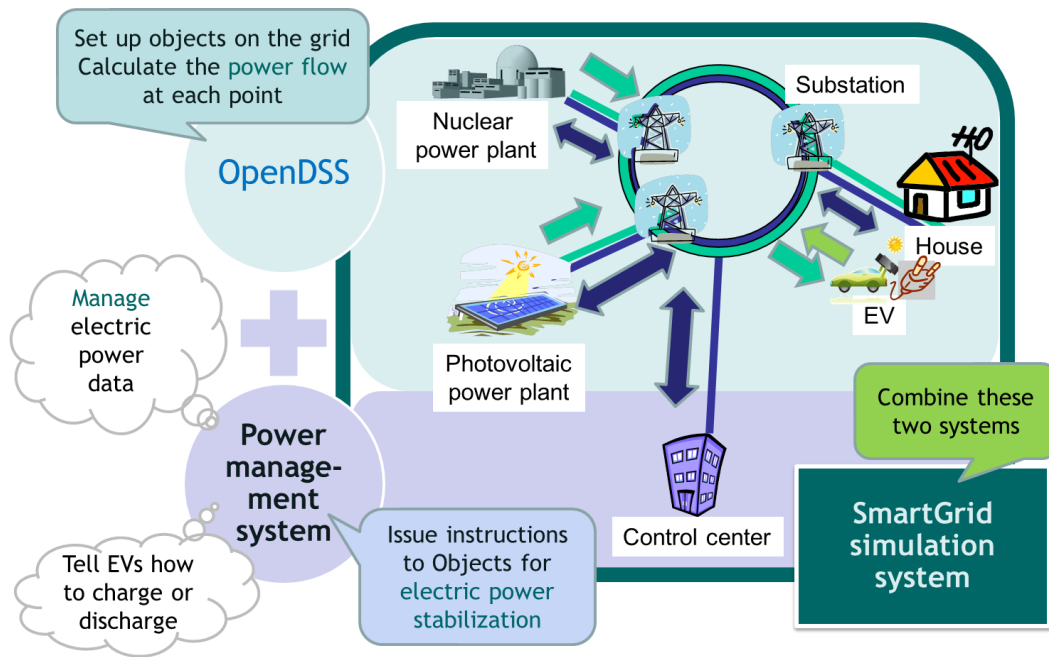
Figure 2. System architecture.

3.3 Work of the Whole System Stabilizing Electric Power

Figure 3 shows the schematic view of a motion of the whole system stabilizing electric power. The power control system collects and manages the information to perform electric power stabilization smoothly, such as the position and battery residual quantity of each EV, and which EV can be used for electric power stabilization. In addition, it collects the data of the electric power and voltage at each point at the setup interval. When an area in which the voltage is less than a proper value is detected, a power control system starts electric power stabilization work that issues instructions to each EV.

Communication method should be implemented to collect status information of the Smart Grid and to carry down the instructions to discharge to each EV. In this system, the simplest network protocol to achieve those objectives is implemented. That is to say, simple point-to-point communication is used to transfer information between the control center and each node, and point-to-multipoint communication is used to broadcast information required at all nodes. Because the volume of information that must be transferred in this case is relatively small, the simple network protocol is good enough. However, in this simulation system, it is possible to replace it to more elaborate network protocols including hierarchical communication mechanisms if necessary.
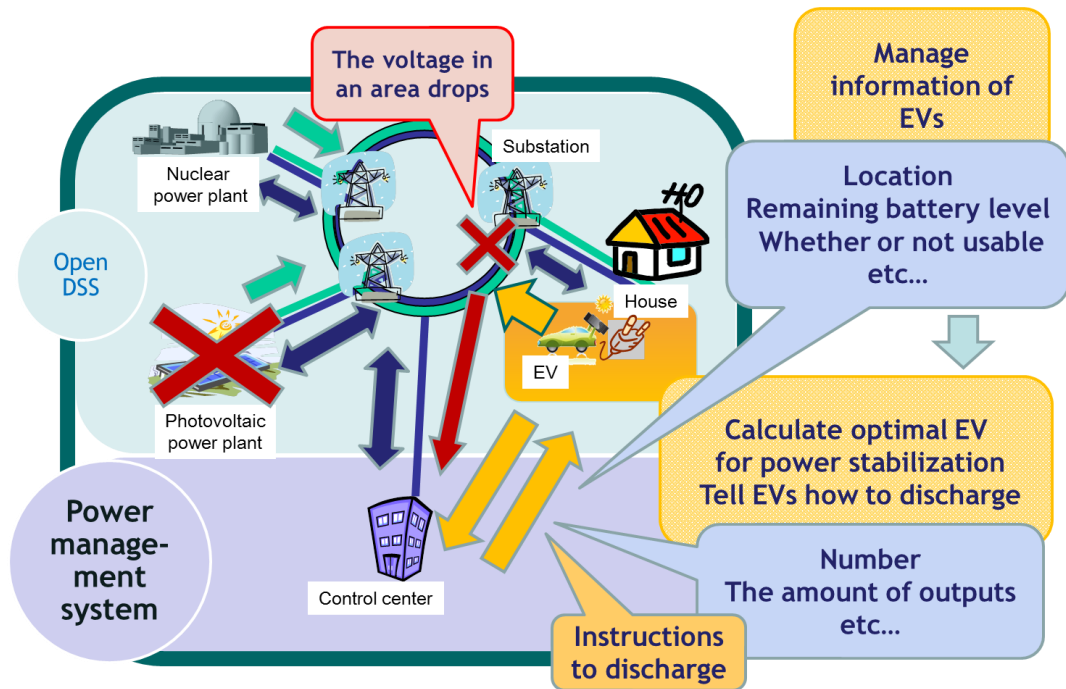
Figure 3. Work of the whole system stabilizing electric power.

3.4 Process inside the Power Control System Stabilizing Electric Power

In this section, we introduce the flow inside the power control system from the automatic decision to issue instructions about electric power stabilization work. The power control system keeps the ideal value of the voltage at each point beforehand, and verify how much difference between the actual value and the ideal value when it observes the behavior of power flow at each point on the grid. By referring the value, it determines which EVs should be used for electric power stabilization and issues instructions to them according to the algorithm chosen by user. Various simulations become possible because user can change objects on the grid, the range of proper voltage, and this algorithm freely. Figure 4 shows the process inside the power control system stabilizing electric power.

Because the algorithm to control the system can be changed freely, it becomes possible to make an experiment to investigate what is the best algorithm to achieve the electric power stabilization, and so on. In the following examples described in Section 4 and 5 in detail, two types of algorithms are implemented that include choosing EVs to discharge at random points and choosing EVs to discharge at selected points. They are examples of algorithm implementation, and it is possible to replace them to other algorithms for evaluation in this simulation system.
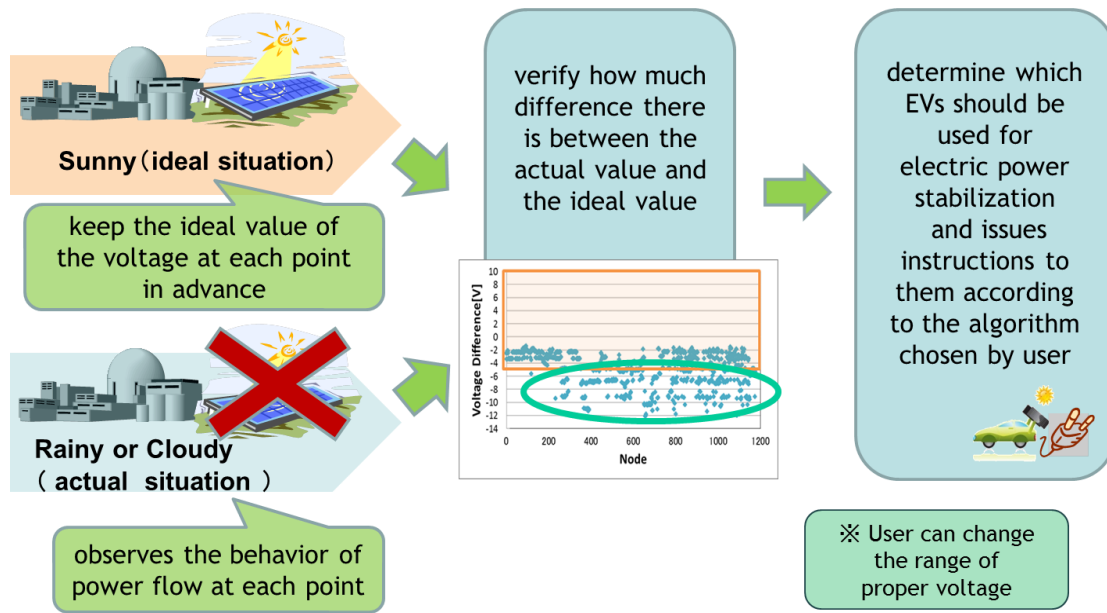
Figure 4. Process inside the power control system stabilizing electric power.

4. Experimental Description

In this chapter, we explain an element to be set up in advance in an experiment such as a power grid model and a packaging method of a photovoltaic power plant and EV.

4.1 Power Grid Model

We experiment using a smart grid simulation system explained in Section 3. The constructed experimental environment was based on a power grid model '8500-Node Test Feeder' (Figure 5) provided by IEEE Power & Energy Society (PES) [12]. This power grid model has 8500 nodes distributed in approximately 10-15 km square. The grid computes power flow based on the specified load. In this model, a voltage source (115 kV, 3,000 MVA) with a three-phase electrical power system and the substations to transform from 115 kV to 120/240 V via 7.2 kV are connected to the power grid. The power transmission method of each end node (120/240 V) is a split-phase electrical distribution system, and the load of each end point is 0.005-93.73 kW. The entire grid has a 10,773 kW load, i.e., a load of approximately 2,000 households.
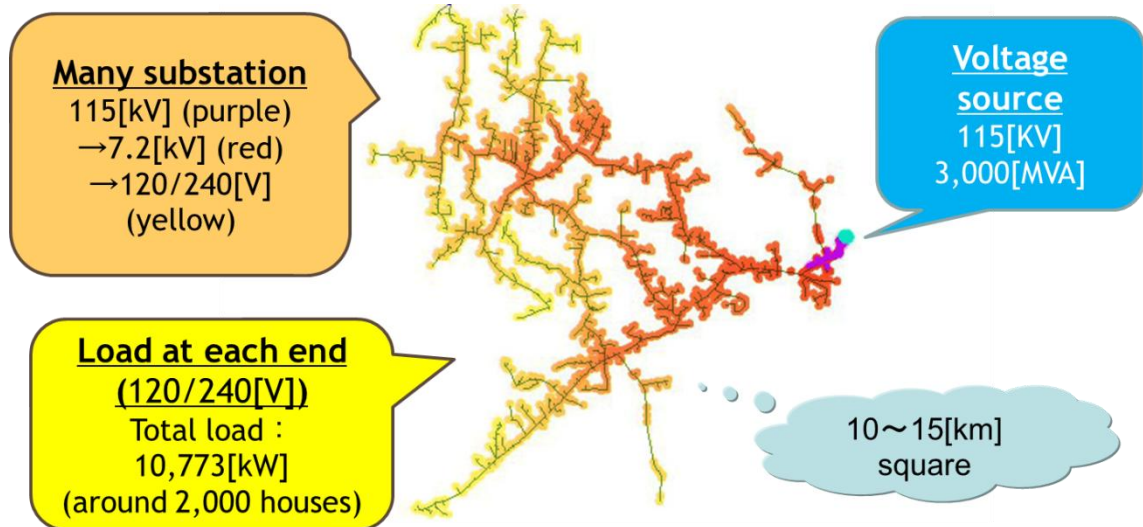
Figure 5. 8500-Node Test Feeder.

4.2 Experiment Environment

A solar power plant (2,400 kW) at one point in a 7.2 kV area was connected to the power grid model introduced in Section 4.1.

Each 2,354 end point in a 120/240 V area has one household, and 50% of the total number of households have a single EV attached. When the electric power on a grid fluctuates abnormally, charging and discharging the EV battery connected to each household stabilizes electric power within the entire grid. Each EV has 25 kWh battery charged fully and each output power is 2 kW. Figure 6 shows the model described above.
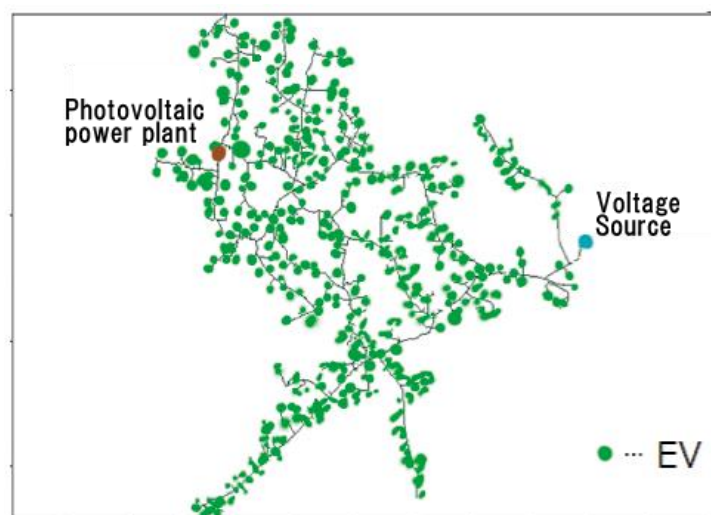
Figure 6. Experimental system.

4.3 Voltage Stabilization by Discharging EV

Prior to this experiment, the change in the number of available EVs as a function of time was surveyed. In this experiment, only EVs connected to households that would not be used as transportation were used as voltage stabilization sources. For simplicity, we assumed that EVs are used for commuting mostly.

We determined the change in the approximate number of EVs as a function of time based on [13] and [14]

Figure 7 shows the percentage of EVs connected to households as a function of time during the course of one day. We built the number of EVs connected to households into the simulation system and conducted a verification experiment to determine how many monitor points voltage drops could be reduced.
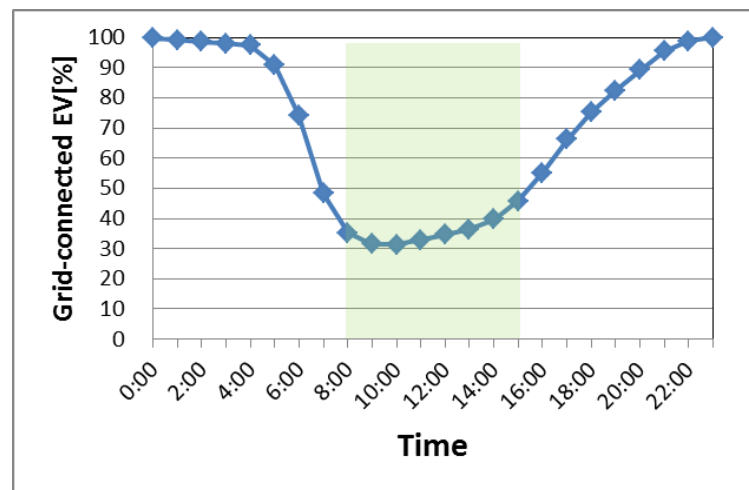
Figure 7. Experimental system.

4.4 Experiment Outline

In this experiment, we further evaluated a situation in which the output of the solar power plant decreased rapidly due to bad weather. Figure 8 shows the power output of the solar power plant. This output curve was created by reference to data collected by the National Institute of Advanced Industrial Science and Technology (AIST) [15]. We assumed that the output power of the solar power plant drops to 0% when it rains. It is assumed that voltage fluctuations occur on the grid when the output from the solar power plant is reduced. Consequently, each EV battery is discharged to compensate for variations in solar power plant output, and electric power within the entire grid is stabilized.
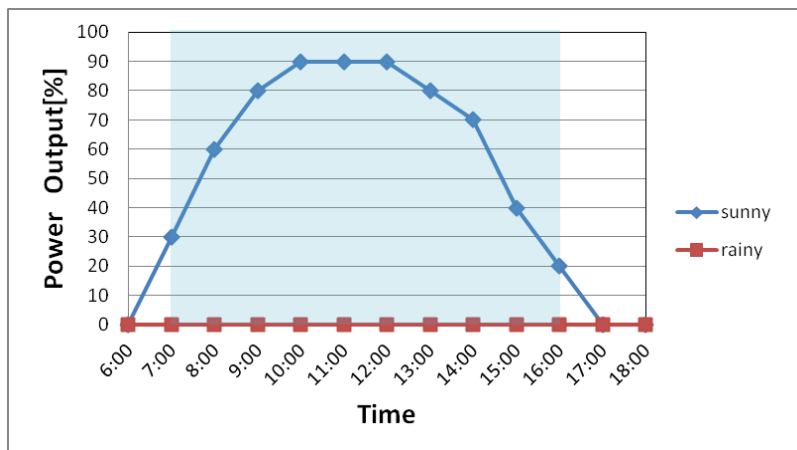
Figure 8. Output of the solar power plant.

In the monitor points at 1,177 substations transforming electric power from 7.2 kV to 120/240 V, we observed to verify voltage fluctuations in the entire power grid resulting from the power output fluctuations at the solar power plant caused by changes in the weather between 7:00 and 16:00. Furthermore, when the power management system judged that the grid have lack of electric power, we evaluate how much a voltage difference would be observed at each point with some electric power stabilization algorithms.

4.5 Voltage Stabilization Algorithm

We set up voltage at each point when the photovoltaic power plant outputs electric power on fine weather as an ideal value to the power management system in advance. We assumed that the voltage was within an adequate range if the voltage difference at each monitor point was 5 V or less with reference to each voltage in the case of fine weather. This range was determined based on the Regulations for Enforcement of the Telecommunications Business Law.

In order to make experiments of the voltage stabilization by EV, we prepared two patterns of algorithms which determine EV to discharge. First algorithm is discharging EVs at the random point and second algorithm is discharging EVs near the point that voltage difference is beyond the adequate value range. We verified how much a voltage difference was observed at each point by changing the position of discharging EV and proved the efficiency of the technique of electric power stabilization.

Figure 9 shows the adequate value range of voltage difference and the point of discharging EV in case of testing second algorithm (discharging EVs near the point that voltage difference is beyond the adequate value range). Each graph shows units of monitor points observing voltage as the abscissa and units of the voltage difference [V] as the ordinate axis. The area colored in orange shows the adequate range in which the voltage difference at each monitor point is 5 V or less with reference to each voltage in the case of fine weather.
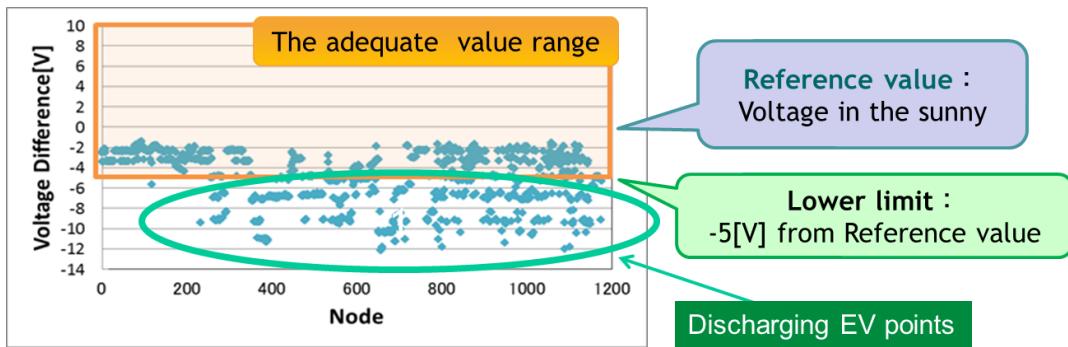
Figure 9. The aptitude range of voltage and the points discharging EVs.

5. Experimental Result with the Constructed Simulation System

5.1 Voltage Variation on the Grid by the Output Difference of the Power Plant

In this section, the monitor points at 1,177 substations transforming electric power from 7.2 kV to 120/240 V were observed to verify voltage fluctuations present in the entire power grid resulting from the power output fluctuations at the solar power plant caused by changes in the weather. Figure 8 shows that each power output difference caused by changes in the weather occurs between 7:00 and 16:00. The simulation system then calculated the voltage difference at each point caused by changes in the weather over time. We verify how much voltage differences arise by change of the weather, and compensates voltage difference by discharging EV.

Figure 10 through Figure 13 show voltage difference at each point every 2 hours between 9:00 and 15:00. Table 1 shows the proportion of the number of points where the voltage differences are identified within the adequate range.

Table 1. Proportion of the number of points within the adequate range [%].

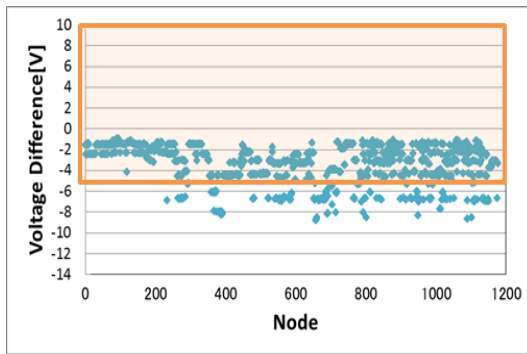| Time	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
Within the normal value range	100.0	82.9	63.4	57.4	57.4	57.4	57.4	68.3	96.8	100.0

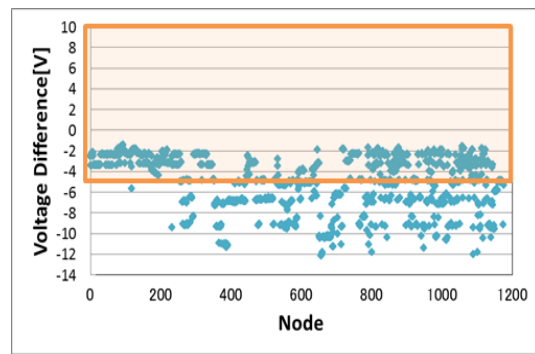Figure 10. Voltage difference (9:00).
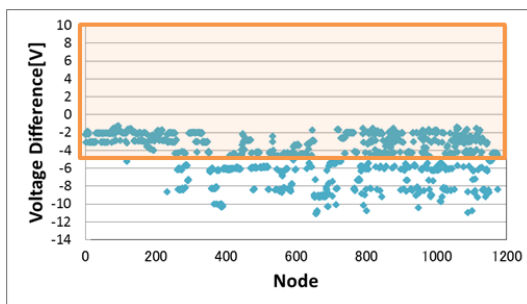

Figure 11. Voltage difference (11:00).

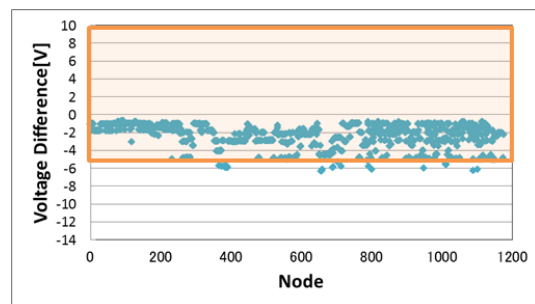Figure 12. Voltage difference (13:00).

Figure 13. Voltage difference (15:00).

Each graph shows units of 1,177 monitor points observing voltage as the abscissa and units of the voltage difference [V] as the ordinate axis. The area colored in orange shows the adequate range in which the voltage difference at each monitor point is 5 V or less with reference to each voltage during the fine weather.

The voltage at each monitor point dropped to a lower value because the output power of the solar power plant decreased to 0% during the bad weather. Between 8:00 and 15:00, the voltage at some points should be raised to the adequate range. The number of deviated points is increased around the noon particularly, as shown in Figure 11 and 12, compared with morning and late afternoon cases shown in Figure 10 and 13. Therefore, discharging EV is necessary for electric power stabilization of the entire grid between 8:00 and 15:00.

5.2 Voltage Variation in the Case of Discharging EVs at Random Points

In this section, we have a verified the reduction of dropped voltage on the entire grid caused by changes in the weather shown in Section 5.1.

In this experiment, EVs were connected at random. The monitor points at 1,177 substations that transform electric power from 7.2 kV to 120/240 V were observed to verify voltage fluctuations present in the entire power grid resulting from the power output fluctuations at the solar power plant caused by changes in the weather. In this experiment, the number of EV which can be used for electric power stabilization is changed according to the data shown in Figure 7. All available EVs discharge. Figure 14 through Figure 17 show

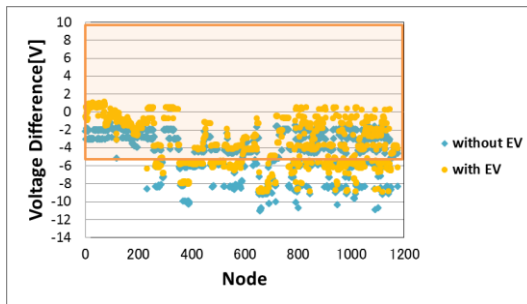voltage difference at each point every 2 hours between 9:00 and 15:00.

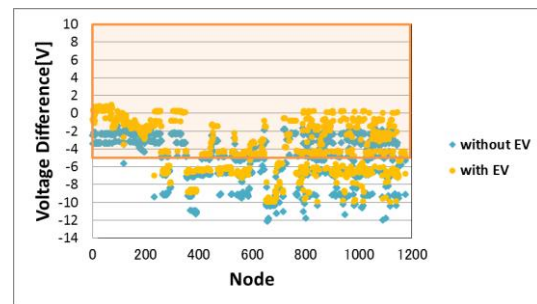Figure 14. Voltage difference (9:00).

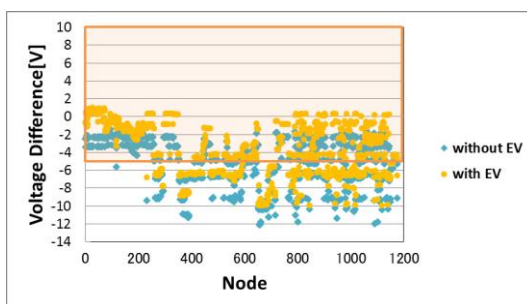Figure 15. Voltage difference (11:00).
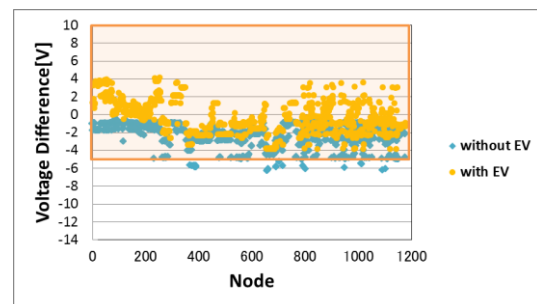

Figure 16. Voltage difference (13:00).

Figure 17. Voltage difference (15:00).

Each graph shows units of 1,177 monitor points observing voltage as the abscissa and units of the voltage difference [V] as the ordinate axis. The area colored in orange shows the adequate range in which the voltage difference at each monitor point is 5 V or less with reference to each voltage in the case of fine weather. Each blue point represents the value of decreased voltage during the bad weather shown in Section 5.1, and each yellow point represents the voltage difference between cases of sunny and bad weather with discharging EV.

These graphs show that the voltage drop can reduce at each point by discharging EV. This method is effective to all the cases shown in Figure 14 through 17 in this evaluation. However, it is necessary to apply the efficient technique of electric power stabilization because voltage should be much raised. In the following section, we verify whether it is possible to increase voltage by changing position of each EV.

5.3 Voltage Variation in the Case of Discharging EVs at Selected Points

In this section, we have verified the reduction of dropped voltage on the entire grid caused by changes in the weather when only position of discharging EV is changed under the same conditions as Section 5.2.

The monitor points at 1,177 substations that transform electric power from 7.2 kV to

120/240 V were observed to verify voltage fluctuations present in the entire power grid resulting from the power output fluctuations at the solar power plant caused by changes in the weather. Similarly, the number of EV which can be used for electric power stabilization is changed according to the data shown in Figure 7. All available EVs discharge. In this experiment, we chose algorithm that set up discharging EVs to the point where the voltage difference is less than the adequate range shown in Section 5.1. Figure 18 through Figure 21 show voltage difference at each point every 2 hours between 9:00 and 15:00.
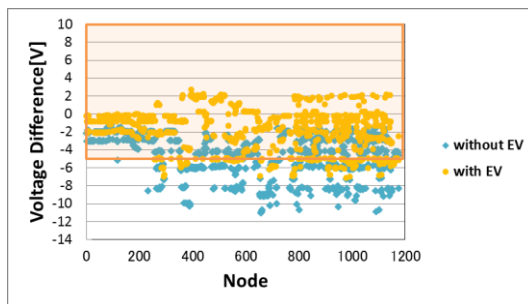

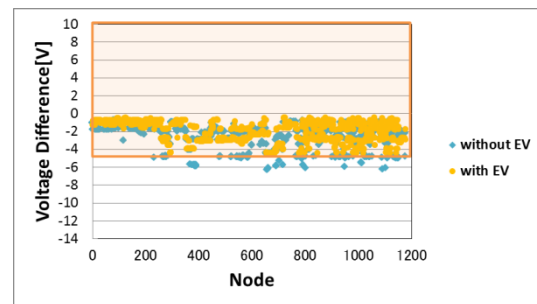
Figure 18. Voltage difference (9:00).
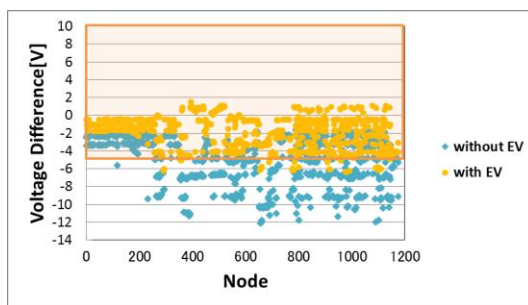
Figure 19. Voltage difference (11:00).

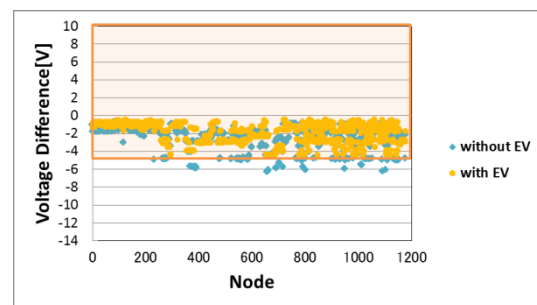Figure 20. Voltage difference (13:00).

Figure 21. Voltage difference (15:00).

Each graph shows units of 1,177 monitor points observing voltage as the abscissa and units of the voltage difference [V] as the ordinate axis. The area colored in orange shows the adequate range in which the voltage difference at each monitor point is 5 V or less with reference to each voltage in the case of fine weather. Each blue point represents the value of decreased voltage during the bad weather shown in Section 5.1, and each yellow point represents the voltage difference between cases of sunny and worsening weather with discharging EV.

These graphs show that the voltage drop can reduce at each point including large voltage difference area. Especially, the status is greatly improved in the cases of a large number of deviations being observed without EV, as shown in Figure 18 and 20. Thus, we verified that the voltage at each point can be efficiently raised by discharging EV targeting the point which is less than the adequate range.

5.4 Discussion

Table 2 shows the proportion of the number of monitor points at which the voltage difference during the bad weather is within the adequate range for 3 cases.

Table 2. Proportion of points within the adequate range with and without EV [%].

Time	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00
Without EV	82.9	63.4	57.4	57.4	57.4	57.4	68.3	96.8
With EV(random)	92.1	67.6	65.0	65.0	65.1	65.0	89.8	100.0
With EV(select)	81.5	82.7	78.9	85.6	93.1	96.7	94.4	100.0

This table shows proportion of points within the adequate range in the case without discharging EV, the case with discharging EV at random point and the case with discharging EV at point selected by chosen algorithm. Discharging EVs increase the proportion of the number of points where the voltage difference is within the adequate range. In the case with discharging EV at point selected by chosen algorithm, it is able to stabilize voltage at each point efficiently by discharging EV at the point beyond the adequate range.

In addition, we verified the current at each point could also be stabilized by issuing directions which reduce voltage difference. Table 3 shows the standard deviation derived from the current difference at each point.

Table 3. Standard deviation derived from the current difference at each point.

Time	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00
Without EV	1.9	2.4	2.7	2.7	2.7	2.4	2.2	1.3
With EV(select)	0.8	1.0	1.2	1.2	1.2	1.0	0.9	0.9

In the case with discharging EV, standard deviation is smaller. This shows that electric power was able to be stabilized because the current margin of increase at each point becomes small.

We can verify the technique to stabilize electric power efficiently by using this simulation system.

6. Conclusion and Future Works

In this paper, we constructed a Smart Grid simulation system with a solar power plant and EVs. We evaluated the effect of the solar power plant and EVs on the power grids by changing the power output of the solar power plant and the number and position of discharging EVs according to time. In addition we examined the efficient interaction of electric energy between the EV batteries and power grid using the simulation. Our results indicated that discharging EVs reduced the voltage drops observed on the entire grid that were caused by weather-related changes.

In the case with discharging EV at point selected by chosen algorithm, it is able to stabilize voltage at each point efficiently by discharging EV at the point beyond the adequate range. In this paper, we prepared the algorithm that is discharging EVs near the point where voltage difference is beyond the adequate value range. Then, we found this is more efficient algorithm to stabilize electric power. We can verify the technique to stabilize electric power efficiently by using this simulation system.

However, it seems that the other situation which was not considered in this system exists. For example, a situation changes by various factors such as the load of the household changed according to time. Moreover, we should explore various factors such as EV which moves by short distance and for a short time and charging EV. The voltage on the grid will change intricately due to add these factors into this system. For the future, we would like to construct and verify the system nearer to real environment by adding a management algorithm that can react quickly to the changing situation.

In the future, it may also be possible to stabilize energy within the system, using information technology control embedded in the network of the Smart Grid.

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